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COMPOSITE SUPERCONDUCTING TRANSITION EDGE BOLOMETER*

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ABSTRACT

A composite far infrared bolometer has been constructed that uses an aluminum film at the superconducting transition temperature of 1.3 K as the temperature sensitive element. The film is evaporated on one edge of a 4×4 mm sapphire substrate, which is coated on the reverse side with an absorbing film of bismuth. The best bolometer has an electrical NEP of $(1.7 \pm 0.1) \times 10^{-15} \text{ W Hz}^{-\frac{1}{2}}$ at 2 Hz, and a specific detectivity, D^* , of $(1.1 \pm 0.1) \times 10^{14} \text{ cm}^{\frac{1}{2}} \text{ W}^{-1} \text{ Hz}^{\frac{1}{2}}$. This measured electrical NEP is within a factor 2 of the fundamental thermal noise limit.

We have developed a composite far infrared bolometer¹ in which the temperature sensitive element is an aluminum film operated at the superconducting transition². The film was deposited on one edge of a sapphire substrate on the reverse side of which was a film of bismuth to absorb far infrared radiation. The measured electrical NEP of the best bolometer was $(1.7 \pm 0.1) \times 10^{-15} \text{ WHz}^{-\frac{1}{2}}$ at 2 Hz, and the corresponding detectivity, $D^* = \epsilon_e (\text{Area})^{\frac{1}{2}} / \text{NEP}$, was $(1.1 \pm 0.1) \times 10^{14} \text{ cm}^{\frac{1}{2}} \text{ W}^{-1} \text{ Hz}^{\frac{1}{2}}$, where $\epsilon_e = 0.47$ is the effective far infrared absorptivity. This electrical NEP was within a factor of 2 of the fundamental thermal noise limit. This performance is the best of any far infrared bolometer reported in the literature.

Each bolometer was fabricated on a single-crystal sapphire substrate with dimensions $4 \times 4 \times 0.135 \text{ mm}$ or $4 \times 4 \times 0.050 \text{ mm}$ (see Fig. 1). Four rectangles of In of size $0.7 \times 0.15 \times 0.0005 \text{ mm}$ were evaporated onto the corners of the substrate, followed by 5 nm of Cu. An Al strip 0.25 mm wide and 50 to 150 nm thick (thermometer) and a Bi strip 0.5 mm wide and 100 nm thick (heater) were evaporated as shown. The edges of the Al strip were cut with a diamond knife to reduce the width of the superconducting transition³ to a few mK. The reverse side of the sapphire was coated with an 80 nm-thick Bi film to absorb far infrared radiation. Films of In 2 μm thick were evaporated onto the In/Cu rectangles, and were cold welded to two 15 μm diameter nylon threads that were also coated with In. The leads supporting the bolometer provided electrical contact to the thermometer and heater, and had a thermal conductance, G , of typically $2 \times 10^{-8} \text{ WK}^{-1}$ at the operating temperature. The nylon

threads were attached to Pb pads mounted on, but electrically insulated from, an OFHC copper mount. Below the mount was a copper block on which was wound a heater. The whole assembly was suspended from the top of a vacuum can by nylon screws so that the bolometer was just below a sapphire vacuum window. This arrangement provided a low-pass filter, with a cut-off frequency of about 10^{-2} Hz, to reduce the effects of temperature fluctuations in the helium bath. Radiation was admitted to the window by a 12 mm diameter stainless steel light pipe that was sealed at the top with a 200 μm -thick black polyethylene sheet. A cooled FluorogoldTM low-pass filter (cut-off $\sim 45 \text{ cm}^{-1}$) was mounted in the liquid helium just above the sapphire window to reduce the background loading on the bolometer. The can was immersed in liquid helium at 1.1 K.

The Al strip formed one arm of a cooled Wheatstone bridge that was operated at 1 kHz. The voltage across the bridge was amplified with a cooled transformer that presented an optimum impedance to a room temperature FET preamplifier with a noise temperature of about 1 K. The 1 kHz signal was lock-in amplified, and the output fed back to the heater on the copper block via a low-pass filter. This negative feedback arrangement was used to maintain the temperature of the bolometer near the midpoint of the superconducting transition, typically 1.25 K, in the presence of slow changes ($< 1 \text{ Hz}$) in the level of the background radiation or in the temperature of the helium bath. At the frequencies at which the radiation was chopped ($> 1 \text{ Hz}$), the feedback was ineffective.

The electrical responsivity, $S(\omega)$, is given by

$$S(\omega) = \left(\frac{\partial V}{\partial P} \right)_I = \frac{(\partial V / \partial T)_I}{G - I(\partial V / \partial T)_I + i\omega C} = \frac{(\partial V / \partial T)_I}{G_e (1 + i\omega \tau_e)} \quad (1)$$

Here, I and V are the current through and the voltage across the Al strip, P is the electrical signal power, $\omega/2\pi = f$ is the chopping frequency, C is the heat capacity of the bolometer, $G_e = G[1 - I(\partial V/\partial T)_I]$ is the effective thermal conductance of the leads, and $\tau_e = C/G_e$ is the effective time constant of the bolometer. The measured parameters of our best bolometer are listed in Table I. Figure 2 shows the measured electrical NEP as a function of frequency. The dashed line was calculated from the sum of the Johnson noise, preamplifier noise, bolometer thermal noise, and bath noise. A spectral density of $1.6 \times 10^{-12} (1 \text{ Hz}^2/f^2) \text{ K}^2 \text{ Hz}^{-1}$ was fitted to the data for the helium bath fluctuations that dominate at low frequencies. Between 1 and 5 Hz, the measured NEP was within a factor two of the thermal noise, $(4k_B T G)^{1/2}$. It is possible that the excess noise arose from the intrinsic thermal fluctuation noise of the Al film⁴. The minimum NEP was insensitive to bias current as would be expected if the noise were dominated by bolometer thermal noise, film thermal noise, or bath noise. As the frequency was increased above about 2 Hz, the NEP degraded slowly because $S(\omega)$ decreased while the Johnson noise and preamplifier noise remained constant.

The dynamic range of the bolometer in a 1 Hz bandwidth at frequencies above 1 Hz was about 10^4 . The feedback system was able to maintain the bolometer at its operating temperature in the presence of slow changes in background loading of up to 1 nW.

For broadband applications, the resistance per square, $R_{\square}$, of the bismuth absorbing film was chosen so that there was no reflection at the bismuth-sapphire interface of radiation incident through the sapphire. This condition is met when⁵ $R_{\square} = Z_0/(n - 1) \approx 190 \Omega/\square$ where $Z_0 \approx 377 \Omega/\square$ is the impedance of free

space, and $n \approx 3$ is the refractive index of sapphire (in practice, the behavior is complicated slightly by the birefringence of sapphire).

The absorptivity of the bismuth/sapphire structure is⁵ then $\epsilon =$

$4(n - 1)/(n + 1)^2 \approx 0.5$. This result was confirmed experimentally by far infrared transmission measurements on bismuth-coated substrates⁶.

We also measured directly the far infrared absorptivity of the bolometer.

In a separate series of experiments, we determined the transmissivities of the light-pipe, black polyethylene sheet, FluorogoldTM filter, and sapphire window. The radiation incident on the black polyethylene sheet was chopped between sources at 77 K and 290 K. We calculated that the spectrum of the radiation incident on the bolometer peaked at about 25 cm^{-1} , with half-power frequencies at 14 cm^{-1} (determined by the spectrum of the incident radiation) and 36 cm^{-1} (determined by the FluorogoldTM filter). The effective absorbing area, A_e , of the bolometer was reduced by about 9% to 14.6 mm^2 by the presence of the In and Al films, which have a low absorptivity in the relevant frequency range. We assumed that a fraction $\epsilon A_e / A_{lp}$ (A_{lp} is the area of the light pipe) of the radiation leaving the light pipe was absorbed by the bismuth film. This calibration procedure led to $\epsilon = 0.52 \pm 0.05$, in good agreement with the theoretical value, and with the value obtained from the transmissivity measurements. The effective absorptivity referred to the area of the entire bolometer, $\epsilon_e = \epsilon (A_e / A)$, was 0.47 ± 0.05 . The detectivity, $D^* = \epsilon_e A^{1/2} / (\text{NEP})$, was $1.1 \times 10^{14} \text{ cm}^{1/2} \text{ W}^{-1} \text{ Hz}^{1/2}$. By choosing the resistivity of the bismuth absorber appropriately, ϵ can be increased to as much as 0.9 for a narrow band of frequencies. D^* would be increased accordingly.

We have demonstrated that the electrical NEP of a superconducting bolometer can be within a factor of 2 of the thermal noise of the bolometer. If a similar limitation can be achieved with a liquid He³ cooled device, a farther improvement in sensitivity is to be expected. For example, we estimate that the heat capacity of a bolometer operated at 0.4 K (approximately the transition temperature of titanium) could be as low as 10^{-10} JK^{-1} . The thermal conductance could be reduced by an order of magnitude to $2 \times 10^{-9} \text{ WK}^{-1}$ while maintaining the same time constant as the present bolometer. The thermal noise limited NEP would then approach $10^{-16} \text{ WHz}^{-\frac{1}{2}}$. In order to achieve this limit, a preamplifier with a noise temperature of less than 0.4 K would be required.

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⁶We are indebted to Dr. G. I. Hoffer for performing these measurements.

Table I. Measured Parameters of Bolometer

Operating temperature	1.27 K
Heat capacity, C	$1.2 \times 10^{-9} \text{ JK}^{-1}$
Thermal conductance, G	$2.0 \times 10^{-8} \text{ WK}^{-1}$
Time constant, τ	60 ms
dR/dT	$200 \text{ } \Omega \text{K}^{-1}$
Bias current, I	5.3 μA rms
Effective thermal conductance, G_e	$1.44 \times 10^{-8} \text{ WK}^{-1}$
Effective time constant, τ_e	83 ms
Responsivity, S(0)	$7.4 \times 10^4 \text{ VW}^{-1}$
Electrical NEP (2 Hz)	$(1.7 \pm 0.1) \times 10^{-15} \text{ WHz}^{-\frac{1}{2}}$
Electrical NEP (5 Hz)	$(2.0 \pm 0.1) \times 10^{-15} \text{ WHz}^{-\frac{1}{2}}$
$(\text{NEP})_{\text{Th}} = (4k_B T^2 G)^{\frac{1}{2}}$	$1.3 \times 10^{-15} \text{ WHz}^{-\frac{1}{2}}$
Dynamic range in 1 Hz bandwidth	10^4
Area of bolometer, A	16 mm^2
Effective absorptivity, ϵ_e	0.47 ± 0.05
$D^* = \epsilon_e A^{\frac{1}{2}} / \text{NEP} (2 \text{ Hz})$	$(1.1 \pm 0.1) \times 10^{14} \text{ cm}^{\frac{1}{2}} \text{ W}^{-1} \text{ Hz}^{\frac{1}{2}}$

Figure Captions

Fig. 1 Configuration of bolometer.

Fig. 2 Measured (●) and calculated (---) electrical NEP.

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